

# Baryon Acoustic Oscillations (BAO) at LBNL

## David Schlegel

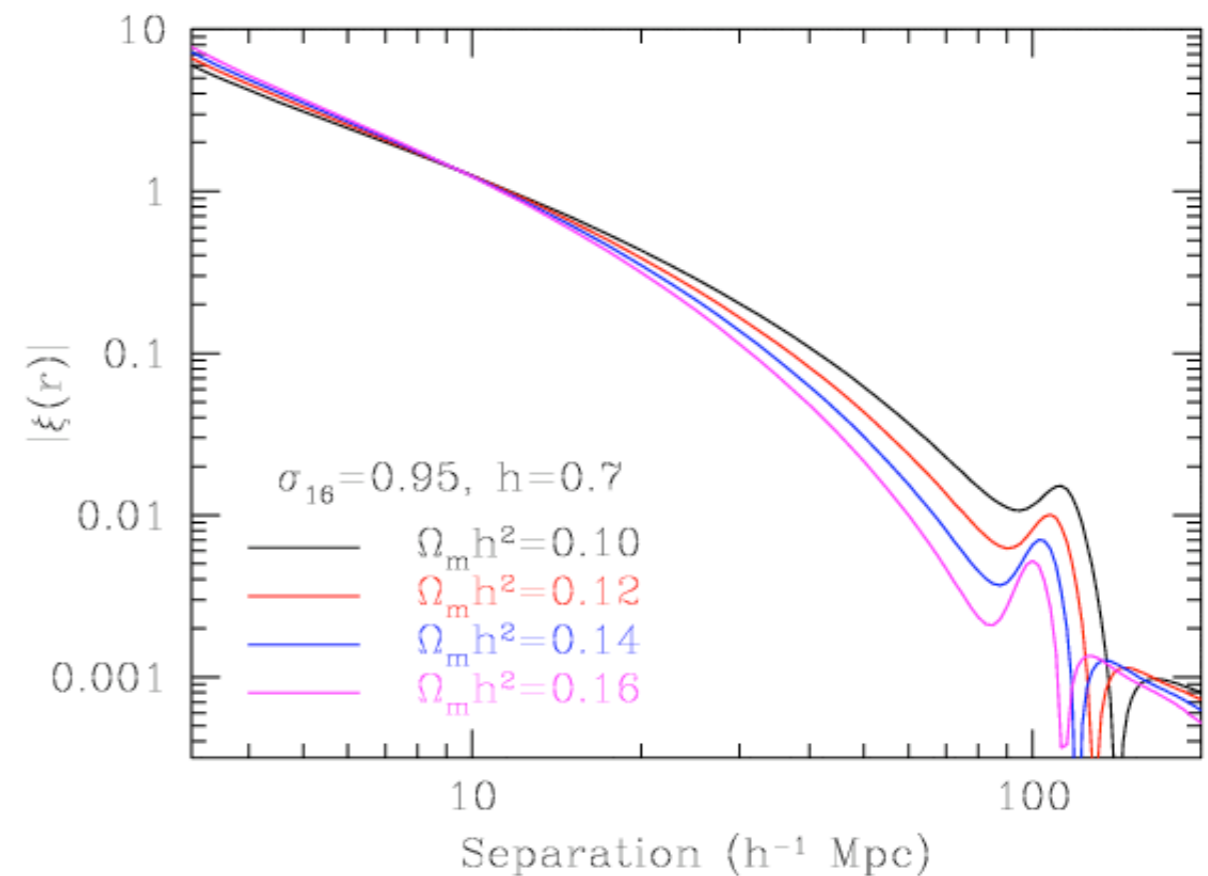
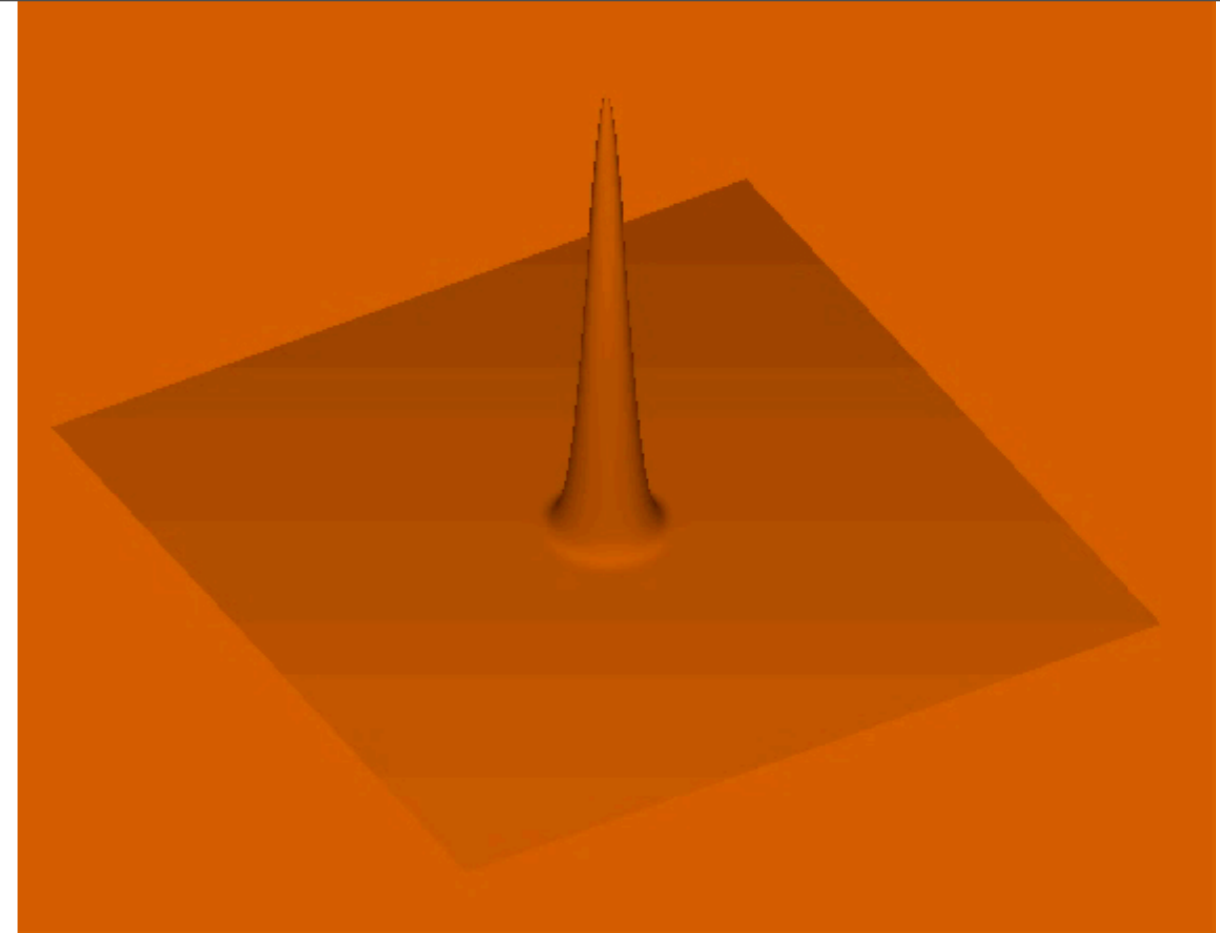
1. What are BAO? How does it measure dark energy?
2. Status of current experiments using the Sloan Digital Sky Survey (SDSS)
3. SDSS-III proposal for precision BAO experiment
4. Next Generation upgrades: automated fiber spectrographs with  $>1000$  fibers

# Acoustic Oscillations

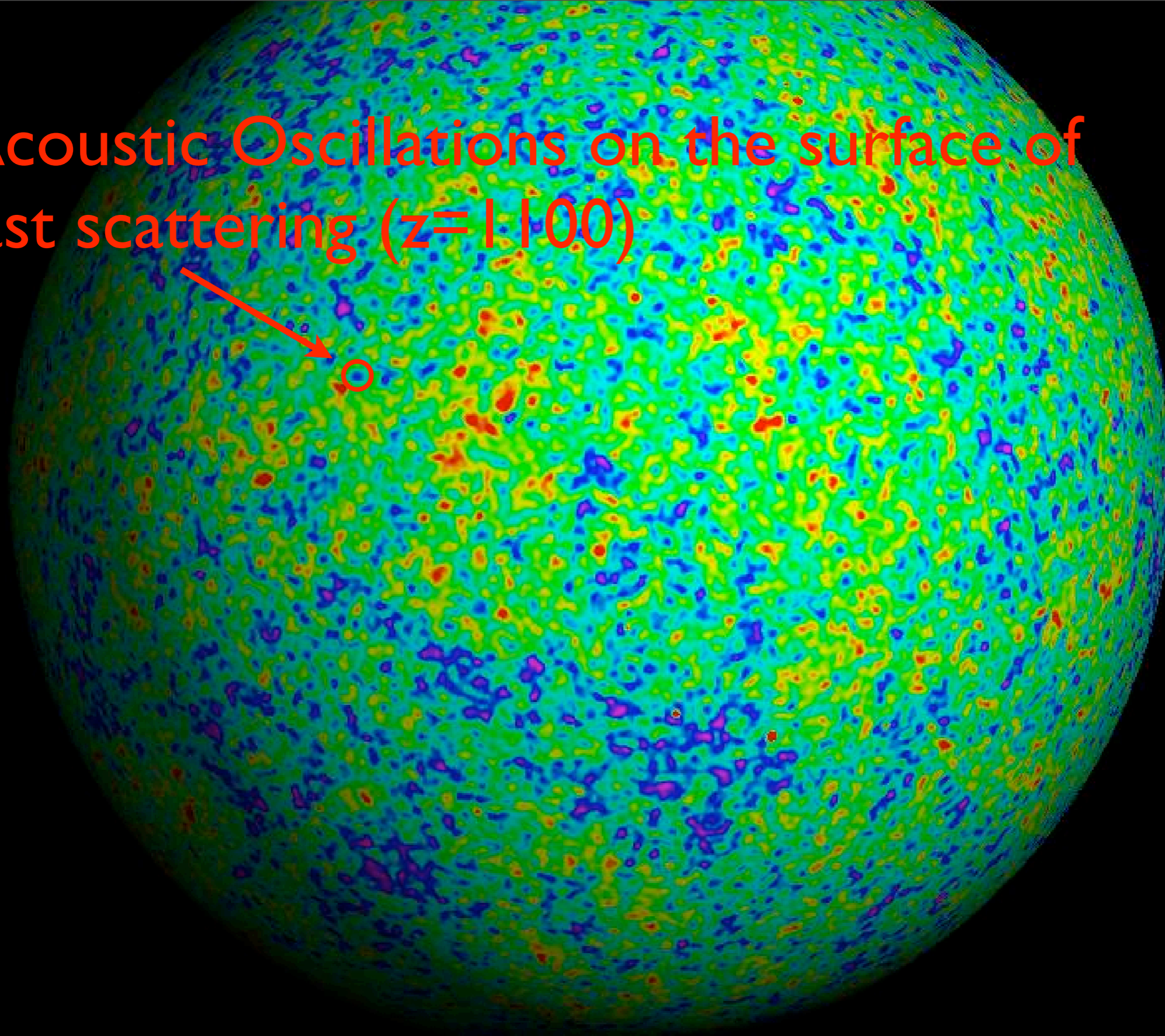
...our newest tool

- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.

standard ruler!



# Acoustic Oscillations on the surface of last scattering ( $z=1100$ )

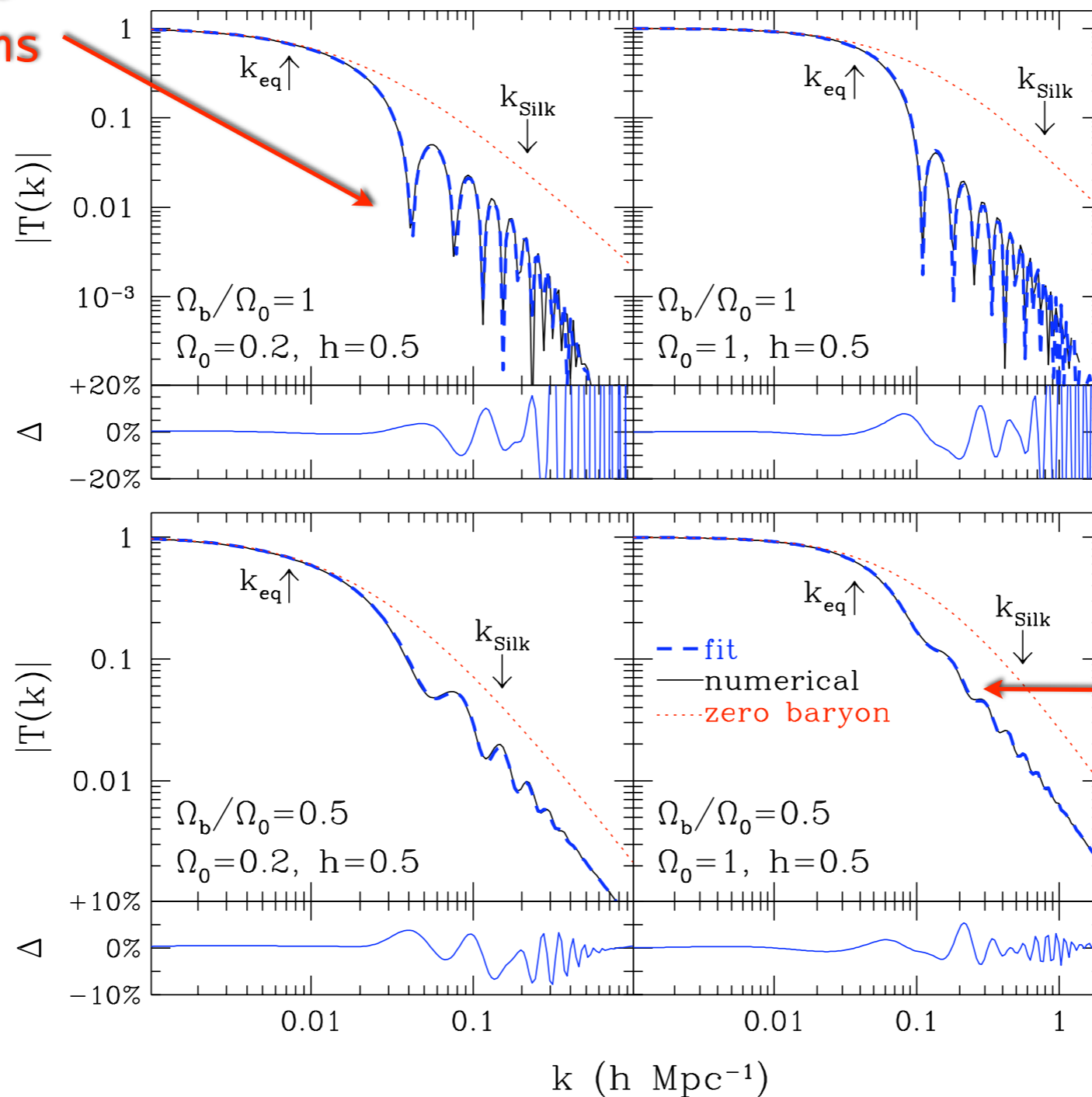


WMAP 1st-year map

Tegmark, Oliveira-Costa, Hamilton (2003)

# Power spectra from galaxy surveys

If the Universe  
were all baryons  
(huge wiggles)

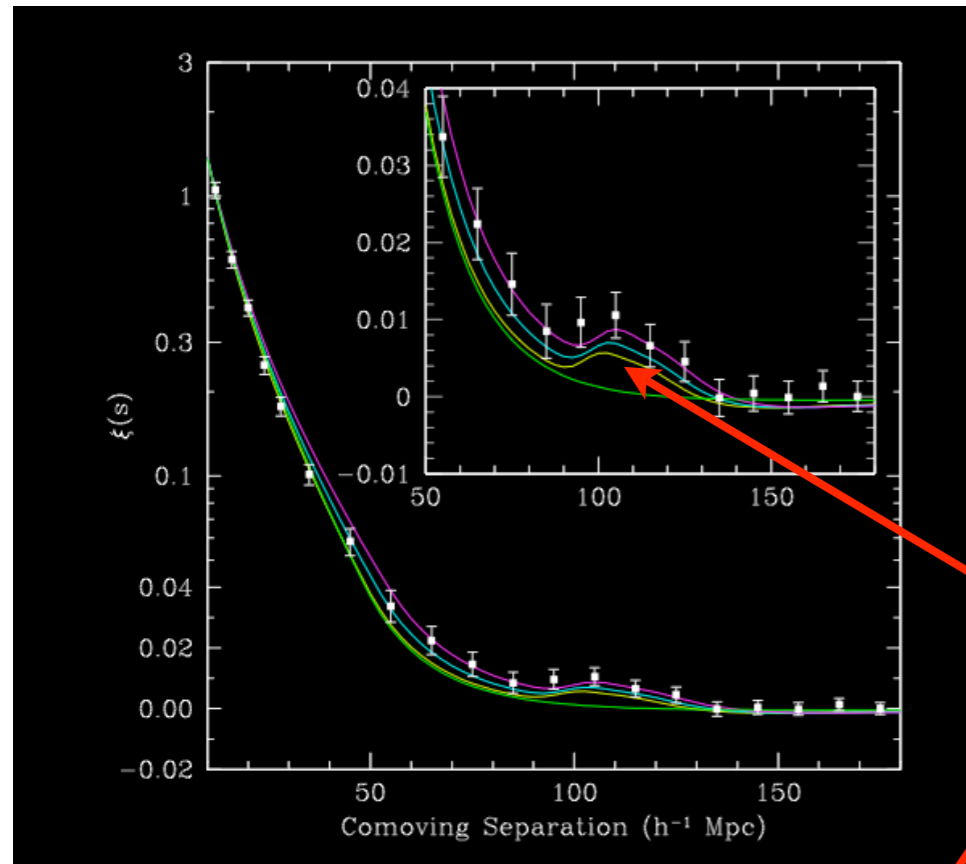


Closer to what we  
expect to see

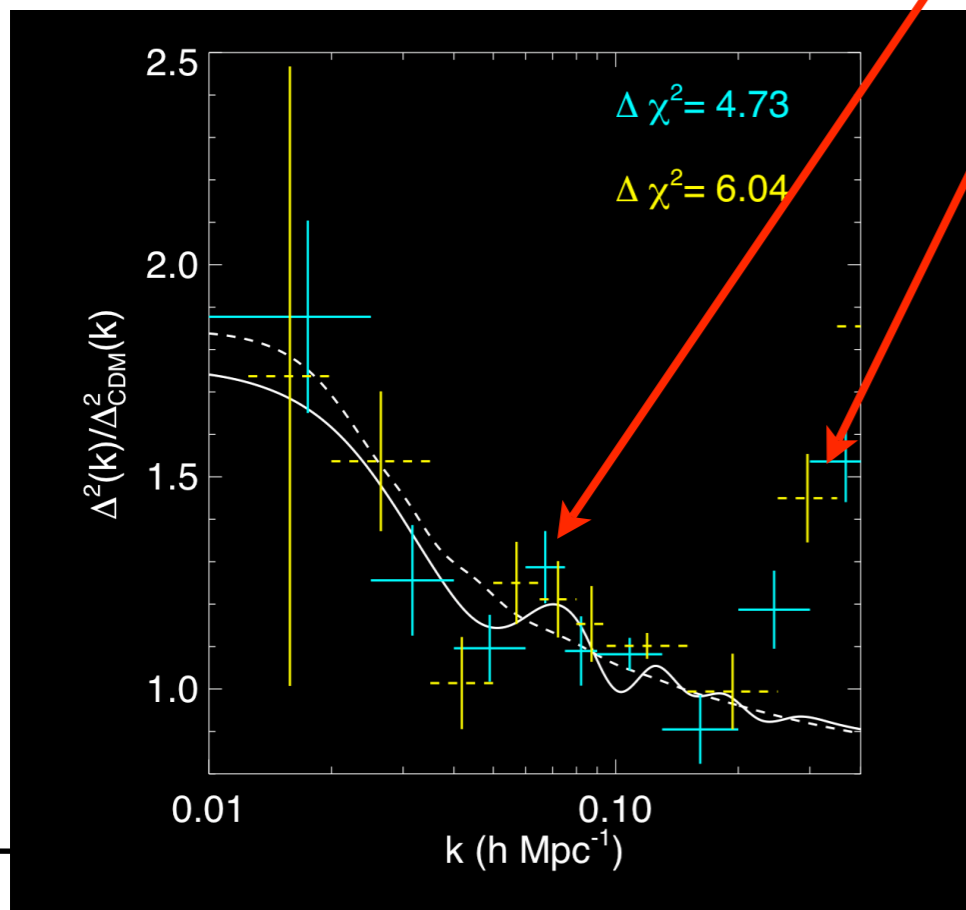
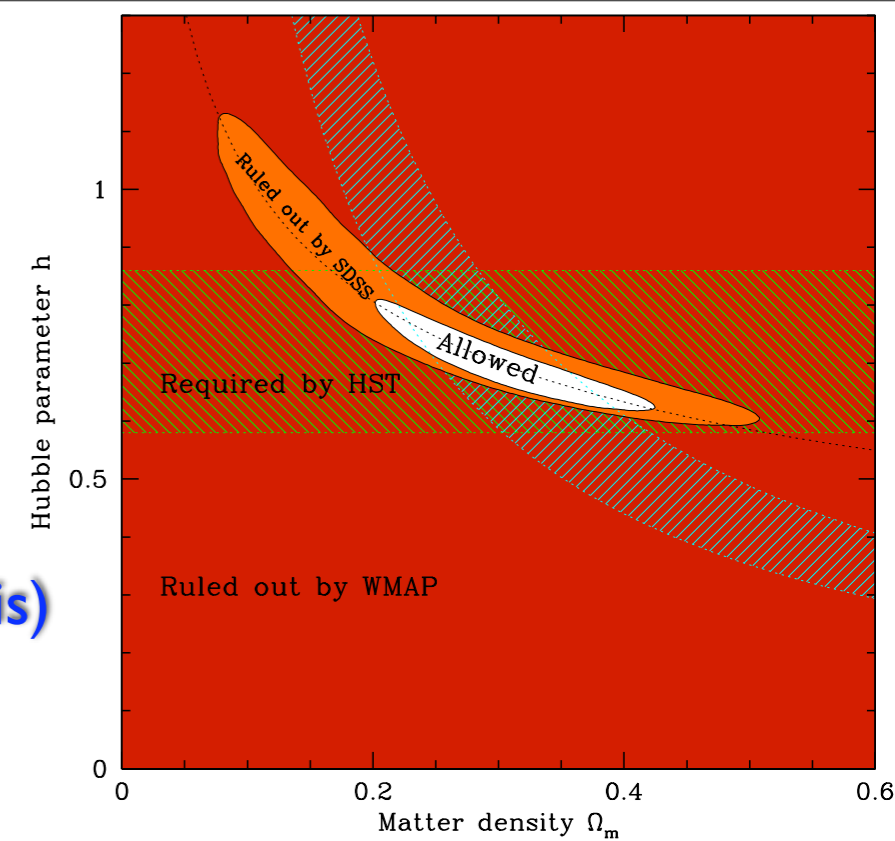
Fig. 3.— Four examples of the fit compared to numerical results. The larger plots show the numerical result (solid) and the fit (dashed). The smaller subplots show the residuals, defined as the difference between the two divided by a non-oscillatory envelope. Note that in the fully baryonic models, the oscillations have alternating sign in the transfer function. Also shown is the zero baryon case (dotted); note the strong suppression on scales below the sound horizon due to the baryons.

From Eisenstein & Hu '97

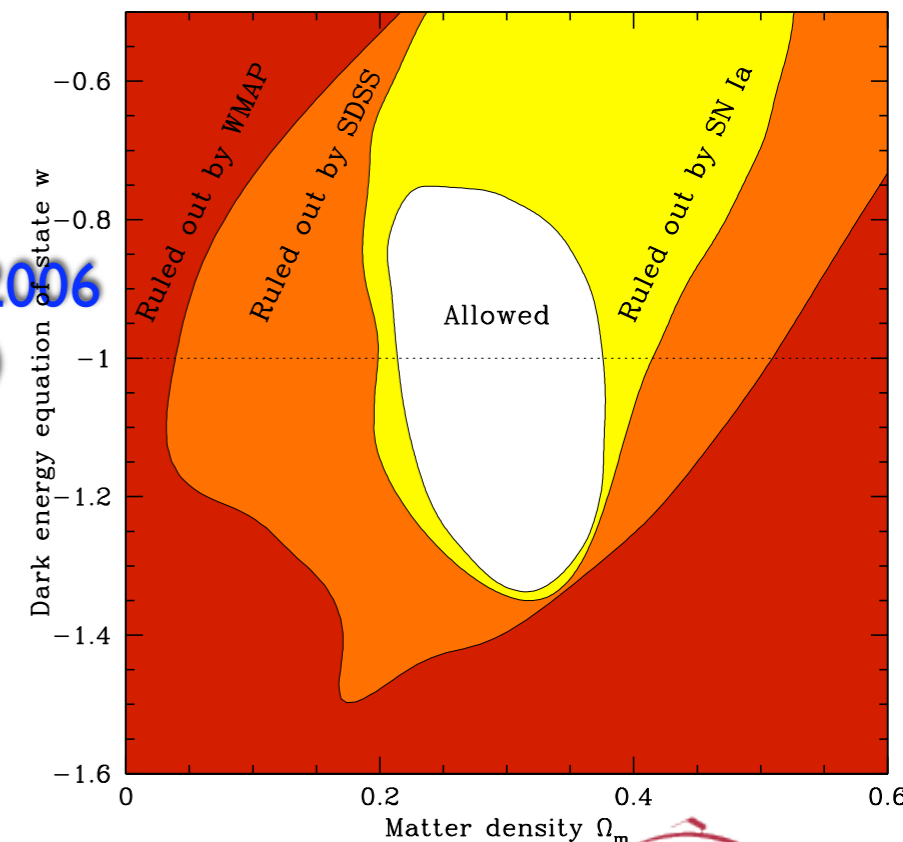
# Baryon acoustic oscillations: First Results



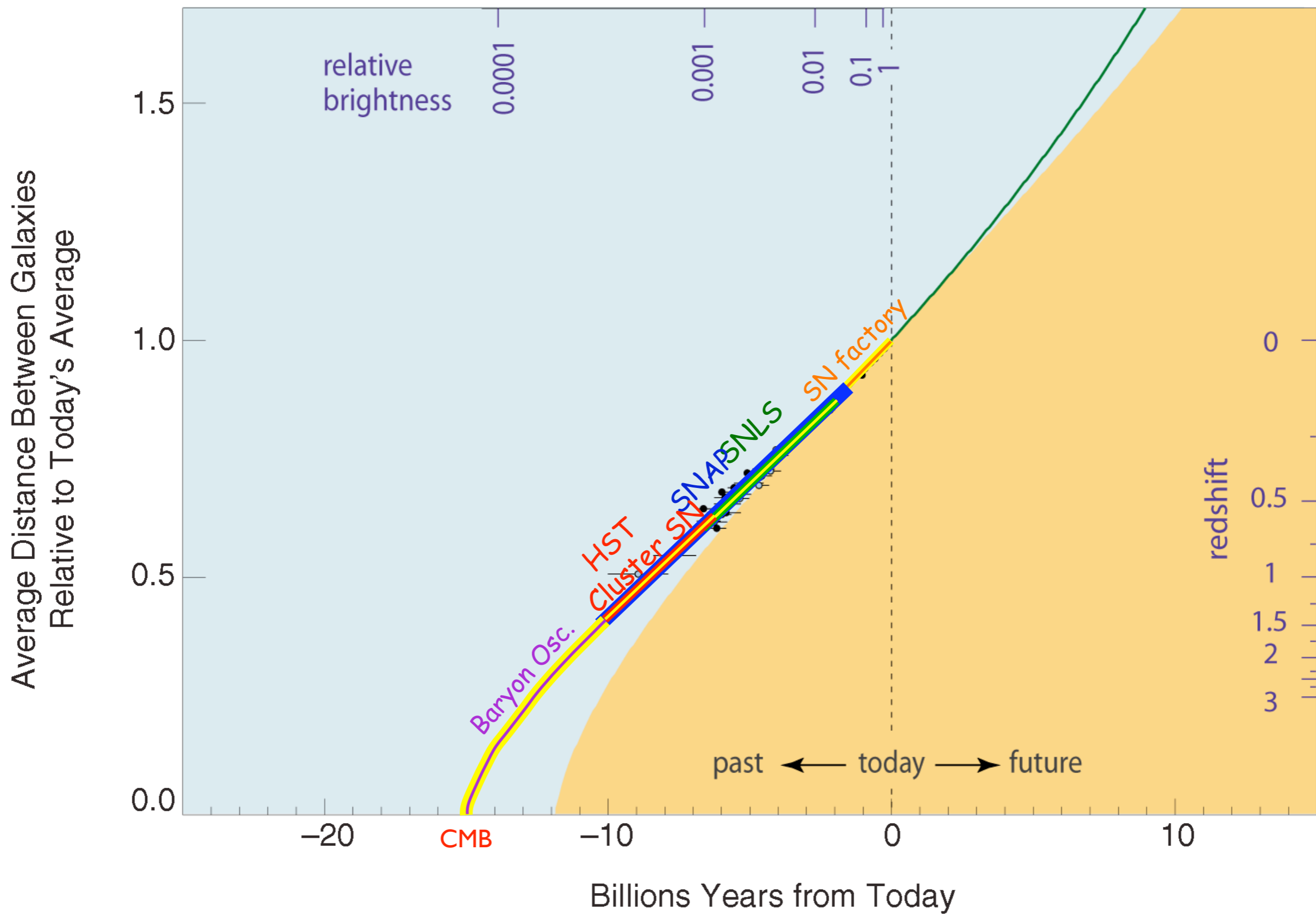
Eisenstein et al. 2005  
SDSS spectro-z  
40,000 red galaxies  
 $0.15 < z < 0.40$   
3.5-sigma detection  
(configuration-space analysis)



Padmanabhan, Schlegel et al 2006  
SDSS photo-z (less accurate)  
600,000 red galaxies  
 $0.15 < z < 0.60$   
2.5-sigma detection  
(power spectrum analysis)



# Expansion History of the Universe



# Dark Energy Task Force findings: (13 Feb 2006)

All are geometric measures of dark energy

I. Four observational techniques dominate White Papers:

a. Baryon Acoustic Oscillations (BAO) large-scale surveys measure features in distribution of galaxies. BAO:  $d_A(z)$  and  $H(z)$ .

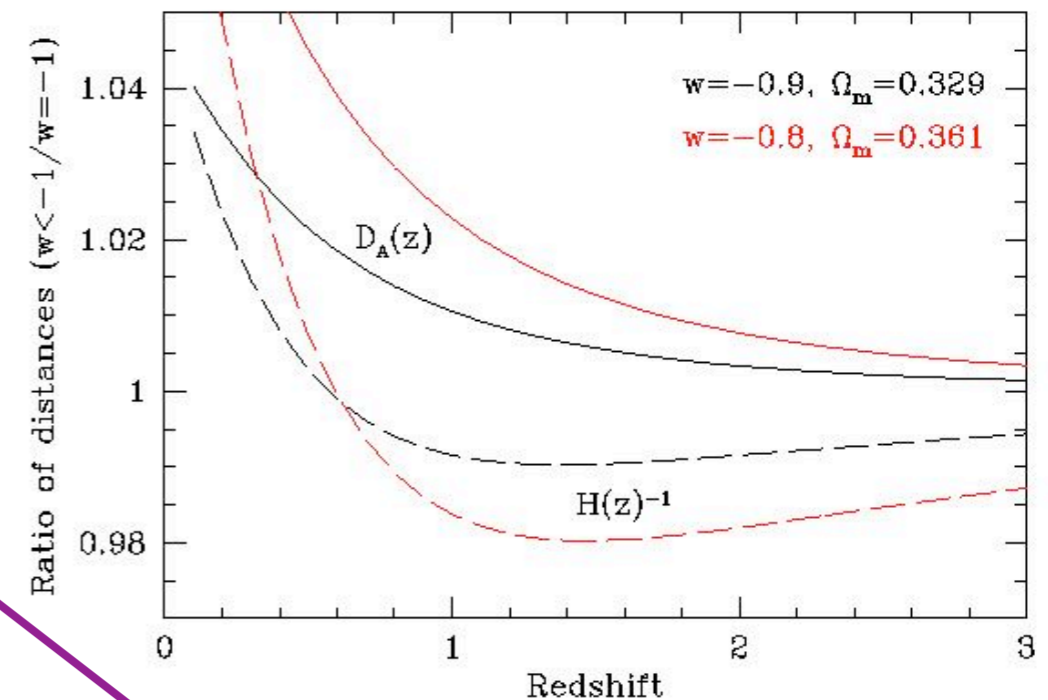
b. Cluster (CL) surveys measure spatial distribution of galaxy clusters. CL:  $d_A(z)$ ,  $H(z)$ , growth of structure.

c. Supernovae (SN) surveys measure flux and redshift of Type Ia SNe. SN:  $d_L(z)$ .

d. Weak Lensing (WL) surveys measure distortion of background images due to gravitational lensing. WL:  $d_A(z)$ , growth of structure.

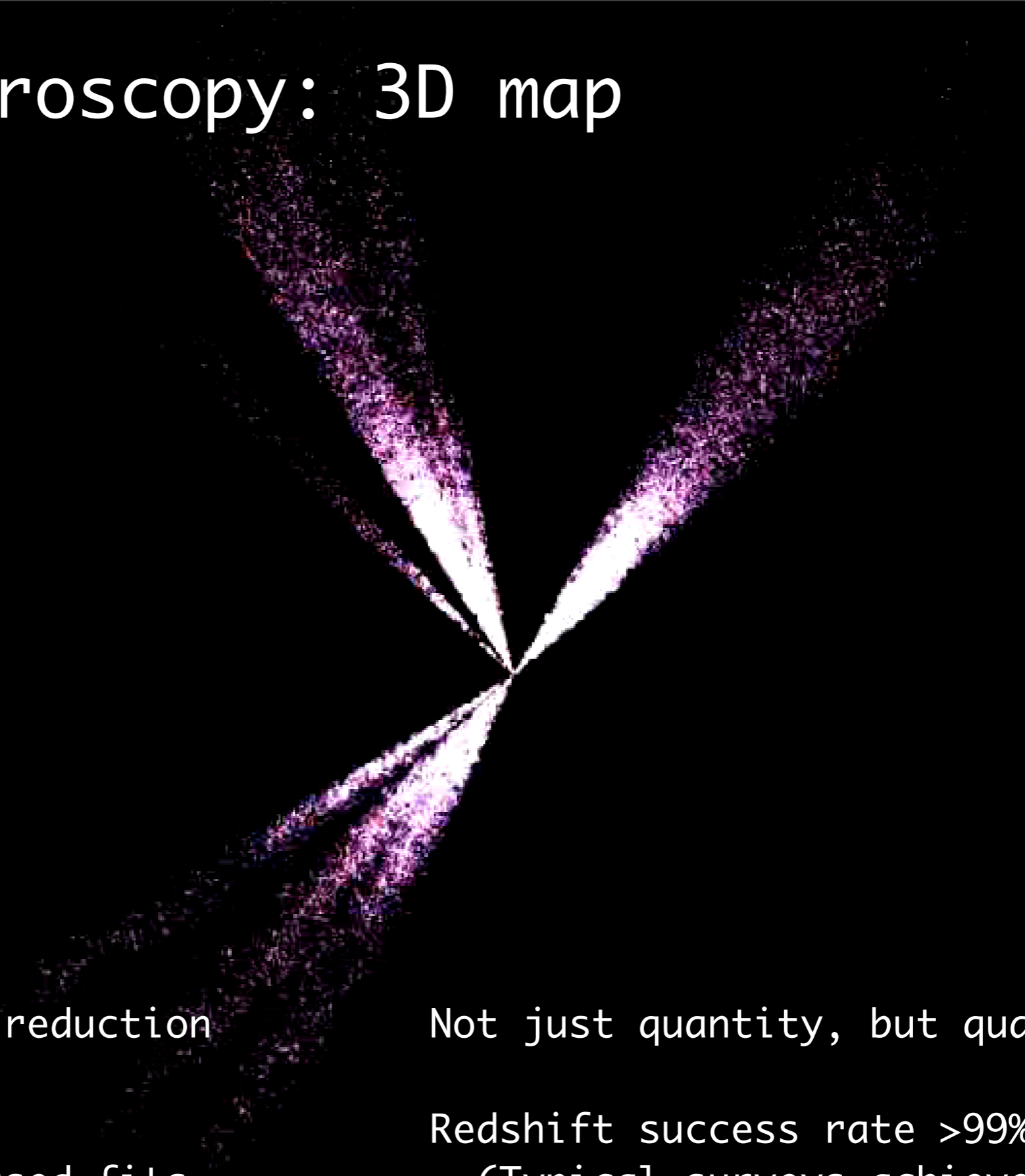
2. Different techniques have different strengths and weaknesses and sensitive in different ways to dark energy and other cosmo. parameters.

3. Each of the four techniques can be pursued by multiple observational approaches (radio, visible, NIR, x-ray observations), and a single experiment can study dark energy with multiple techniques. Not all missions necessarily cover all techniques; in principle different combinations of projects can accomplish the same overall goals.



These two methods not yet proven, and complicated by astrophysics (details + evolution of structure formation)

# SDSS Spectroscopy: 3D map



Fully-automated data reduction  
(Burles & Schlegel)

Redshifts from PCA-based fits  
to stellar populations  
(Schlegel '06)

Not just quantity, but quality!

Redshift success rate >99% !!  
(Typical surveys achieve ~70%)  
All errors well-understood.

# Sloan Digital Sky Survey (SDSS)

- Largest survey to date in area + volume
- Completed 10,000 deg<sup>2</sup> imaging in 5 colors (ugriz-bands) from drift-scanning
- Follow-up spectroscopy of 800,000 “main” galaxies to  $z \sim 0.15$
- 80,000 luminous red galaxies to  $z \sim 0.4$
- 60,000 QSOs to  $z \sim 4$
- **Key project : Large scale structure + cosmology**



The SDSS 2.5-m Telescope  
Apache Pt., NM

## Timeline:

2000-2005: SDSS-I, completed

2005-2008: SDSS-II, in progress: legacy survey, supernova search, Milky Way

2006: ARC call for proposals for future uses of Sloan telescope; **BAO**  
**proposal submitted in July 2006; decisions on 13 Nov 2006**

**2008-2013: SDSS-III**

# Recent related publications

- *The Clustering of Photometric Luminous Red Galaxies in the Sloan Digital Sky Survey*, MNRAS 2006, Padmanabhan, Schlegel, et al.
- *Simulations of Baryon Oscillations*, Astropart Phys 2006, Huff, Schulz, White, Schlegel, Warren
- *Correlating the CMB with luminous red galaxies: The integrated Sachs-Wolfe effect*, Phys Rev D 2006, Padmanabhan, Hirata, Seljak, Schlegel, et al.
- *Going nonlinear with Dark Energy Cosmologies*, Phys Rev D 2005, Linder & White
- *Calibrating photometric redshifts of luminous red galaxies*, MNRAS 2005, Padmanabhan, Schlegel, et al
- *Baryon Oscillations*, Astropart Phys 2005, White
- *Cross-correlation of CMB with large-scale structure: Weak gravitational lensing*, Phys Rev D 2004, Hirata, Padmanabhan, Seljak, Schlegel, Brinkmann
- *Sloan Digital Sky Survey Imaging of Low Galactic Latitude Fields: Technical Summary and Data Release*, AJ 2004, Finkbeiner, Padmanabhan, Schlegel, et al.
- *SDSS data management and photometric quality assessment*, AN 2004, Ivezić, Lupton, Schlegel et al.

# Proposal submitted to ARC in July 2006

Strong support from LBL and many other institutions.

They own the telescope

## Refining the Distance Scale to 1% with the ARC 2.5-m Telescope

David Schlegel<sup>1</sup>, Daniel Eisenstein<sup>2</sup>, James Annis<sup>3</sup>, Neta Bahcall<sup>4</sup>, Bruce Bassett<sup>5</sup>, Chuck Bennett<sup>6</sup>, Michael Blanton<sup>7</sup>, Francisco Javier Castander<sup>8</sup>, Masataka Fukugita<sup>9</sup>, James Gunn<sup>4</sup>, Pat Hall<sup>10</sup>, Tim Heckman<sup>5</sup>, Wayne Hu<sup>13</sup>, Zeljko Ivezic<sup>11</sup>, Benjamin Koester<sup>12,13</sup>, Jill Knapp<sup>4</sup>, Guinever Kauffmann<sup>14</sup>, Robert Lupton<sup>4</sup>, Rachel Mandelbaum<sup>4</sup>, Patrick McDonald<sup>15</sup>, Robert Nichol<sup>16</sup>, Nikhil Padmanabhan<sup>1,4</sup>, Saul Perlmutter<sup>1</sup>, Gordon Richards<sup>6</sup>, Adam Riess<sup>6,17</sup>, Natalie Roe<sup>1</sup>, Connie Rockosi<sup>18</sup>, Roman Scoccimarro<sup>7</sup>, David Spergel<sup>4</sup>, Michael Strauss<sup>4</sup>, Nao Suzuki<sup>1</sup>, Alex Szalay<sup>6</sup>, Istvan Szapudi<sup>19</sup>, Max Tegmark<sup>20</sup>, David Weinberg<sup>21</sup>, Martin White<sup>1</sup>, Simon White<sup>14</sup>, Idit Zehavi<sup>22</sup>

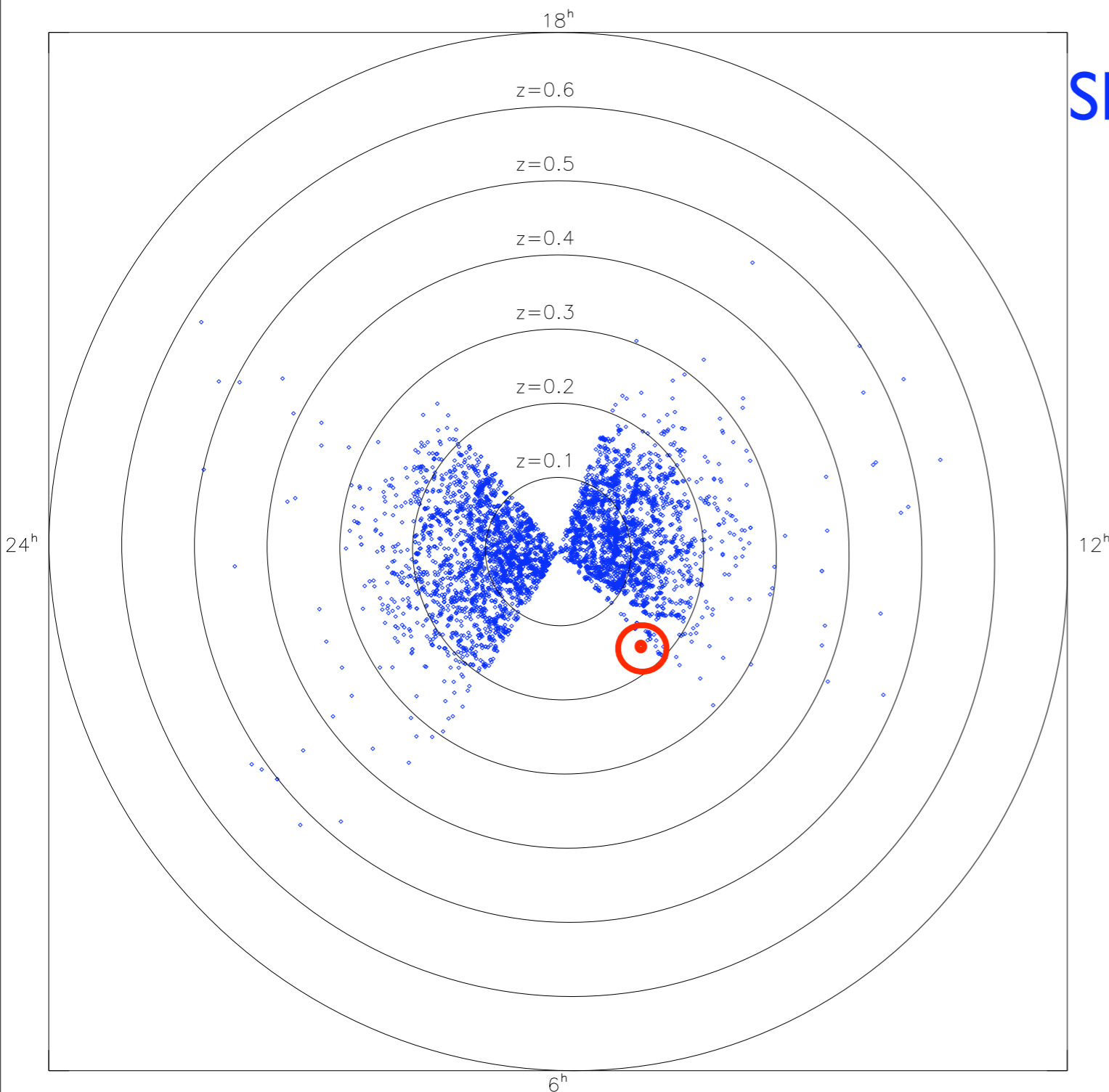
<sup>1</sup>*Lawrence Berkeley National Laboratory*, <sup>2</sup>*University of Arizona*, <sup>3</sup>*Fermi National Accelerator Laboratory*,  
<sup>4</sup>*Princeton University*, <sup>5</sup>*University of Cape Town*, <sup>6</sup>*Johns Hopkins University*, <sup>7</sup>*New York University*,  
<sup>8</sup>*Institut d'Estudis Espacials de Catalunya*, <sup>9</sup>*University of Tokyo*, <sup>10</sup>*York University*,  
<sup>11</sup>*University of Washington*, <sup>12</sup>*University of Michigan*, <sup>13</sup>*University of Chicago*, <sup>14</sup>*Max Planck Institut für Astrophysik*,  
<sup>15</sup>*Canadian Institute for Theoretical Astrophysics*, <sup>16</sup>*University of Portsmouth*, <sup>17</sup>*Space Telescope Science Institute*,  
<sup>18</sup>*University of California at Santa Cruz*, <sup>19</sup>*University of Hawaii*,  
<sup>20</sup>*Massachusetts Institute of Technology*, <sup>21</sup>*The Ohio State University*, <sup>22</sup>*Case Western Reserve University*

## ABSTRACT

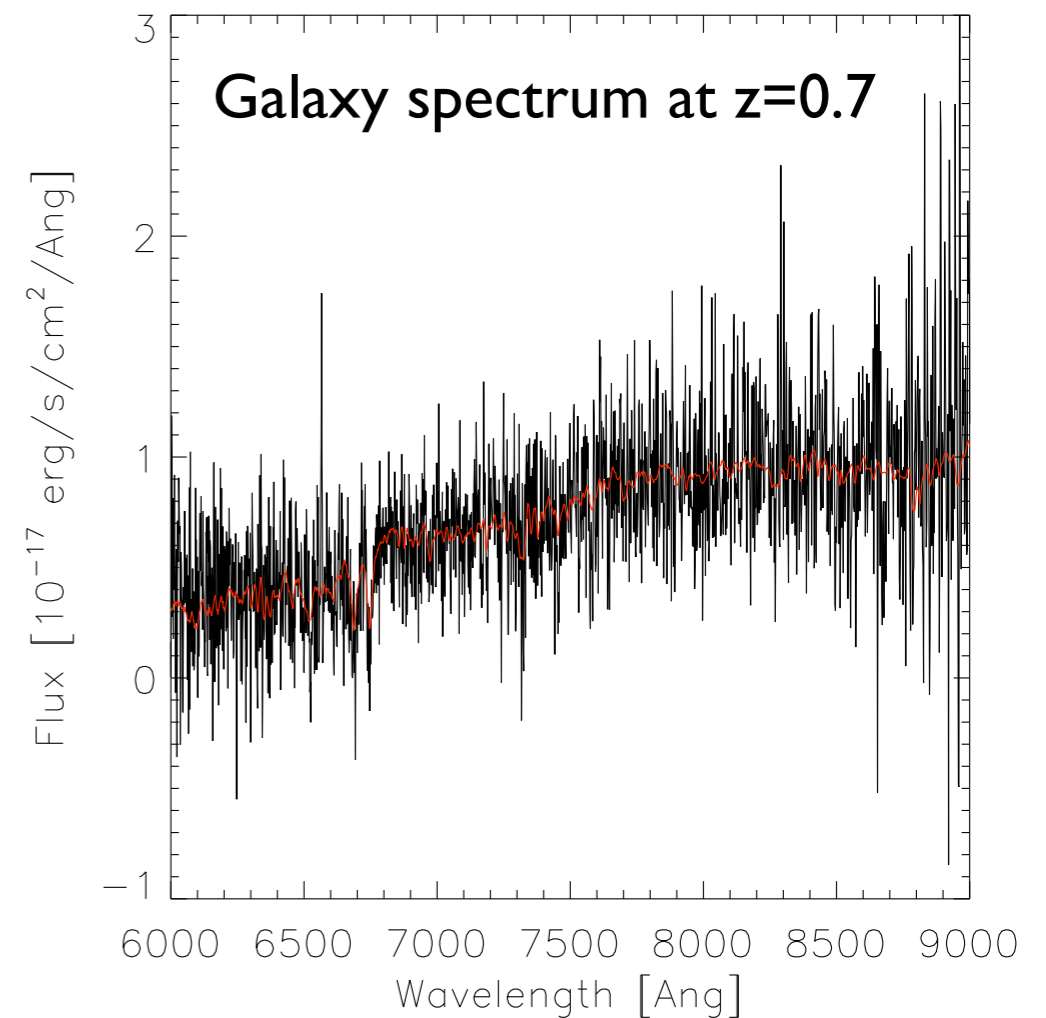
We propose to use the SDSS facility post-2008 to conduct the largest spectroscopic survey to date of cosmological large-scale structure. The survey is designed to use the baryon acoustic oscillation phenomenon to make significant improvements in our measurements of the cosmic distance scale and hence the acceleration of the expansion rate of the Universe. The primary goal is a survey of Luminous Red Galaxies (LRGs) out to  $z \approx 0.7$  over 10,000 square degrees, aimed at the measurement of the baryon acoustic peak in the large-scale galaxy correlations.

# Baryon acoustic oscillations:

The tool is large galaxy redshift surveys.

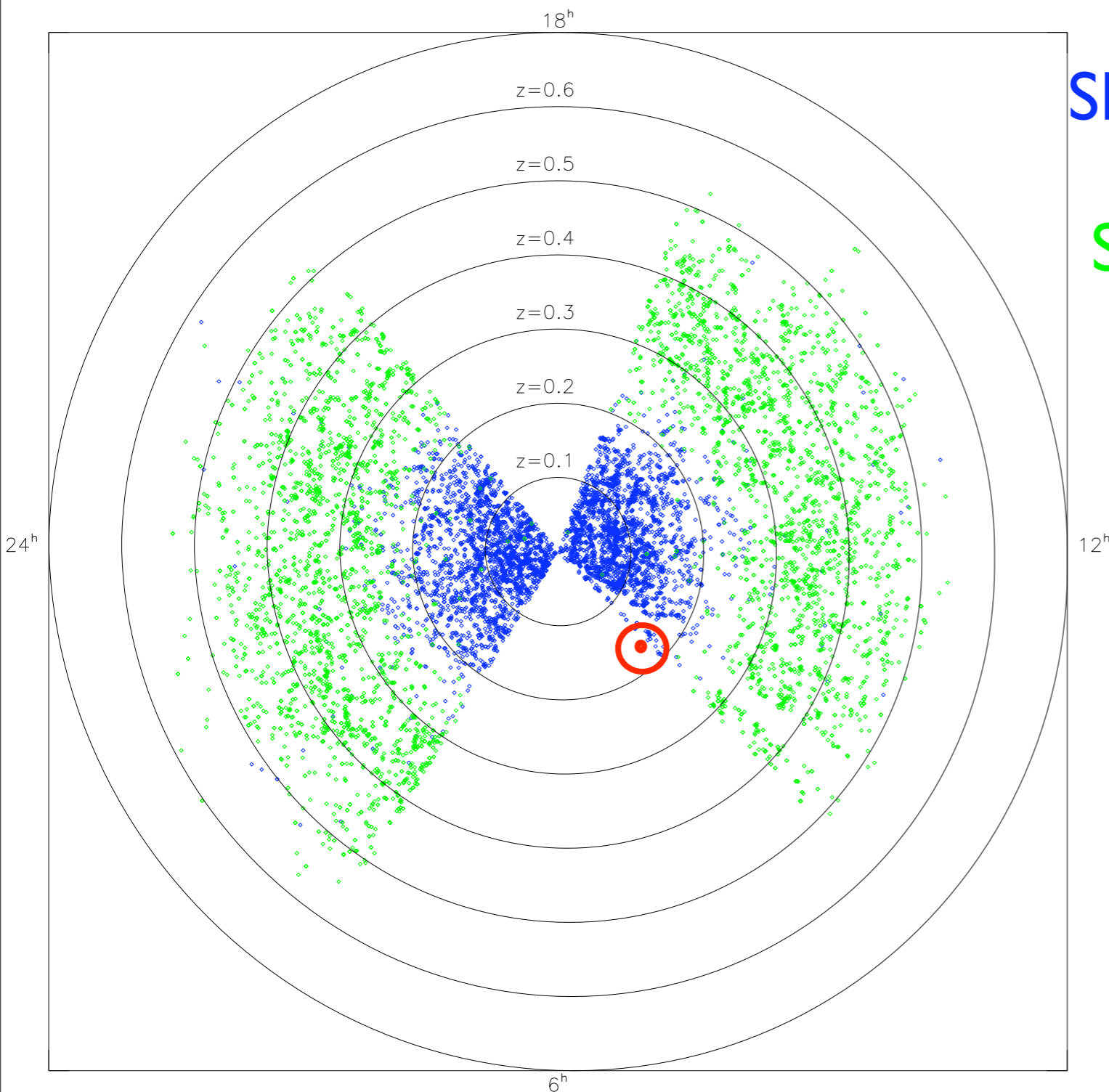


SDSS main survey (too small!)



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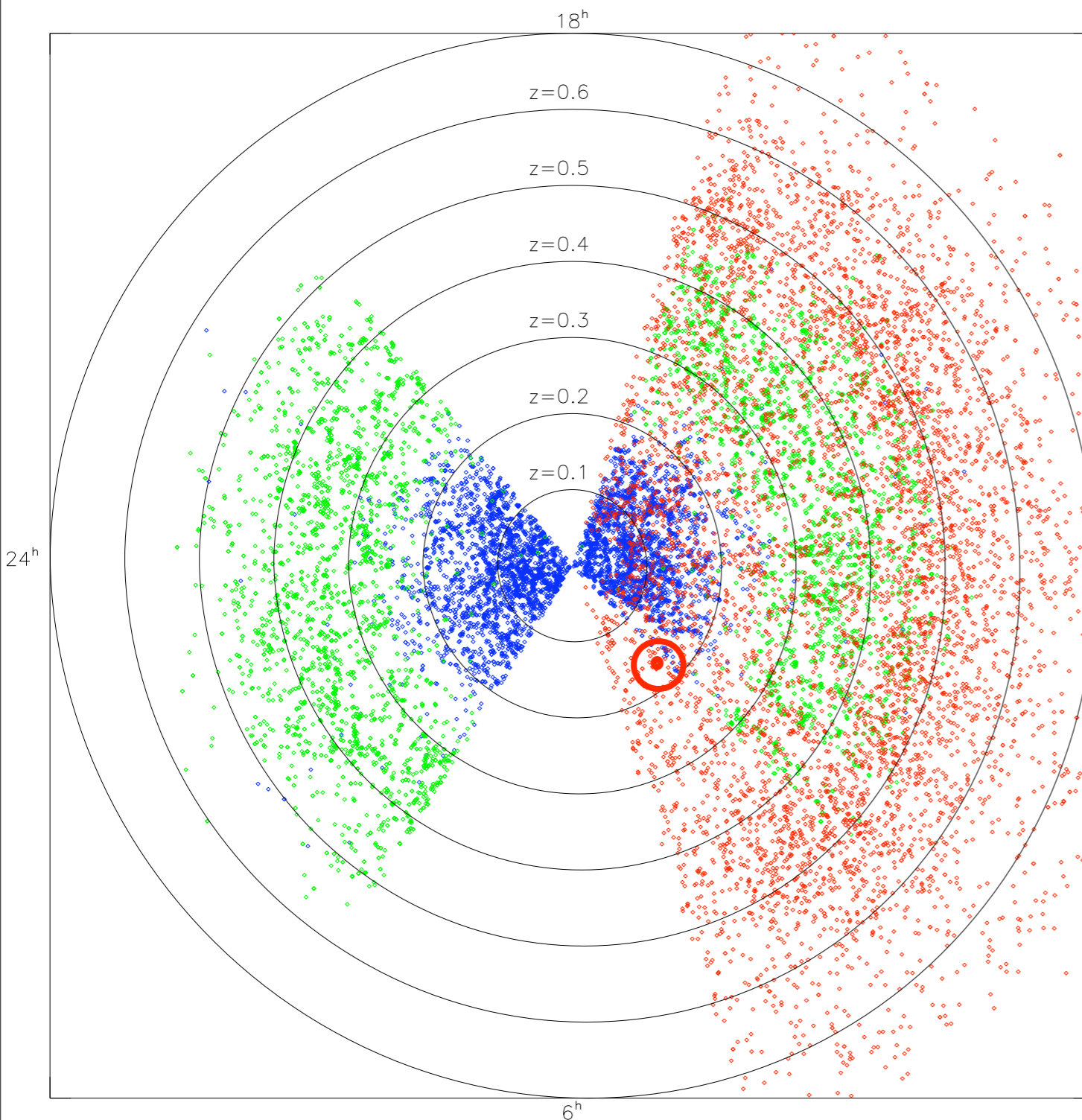


SDSS main survey (too small!)

SDSS-I + SDSS-II red galaxies  
8000 deg<sup>2</sup> (finish in 2008)  
samples  $10^{-4}$  galaxies/Mpc<sup>3</sup>

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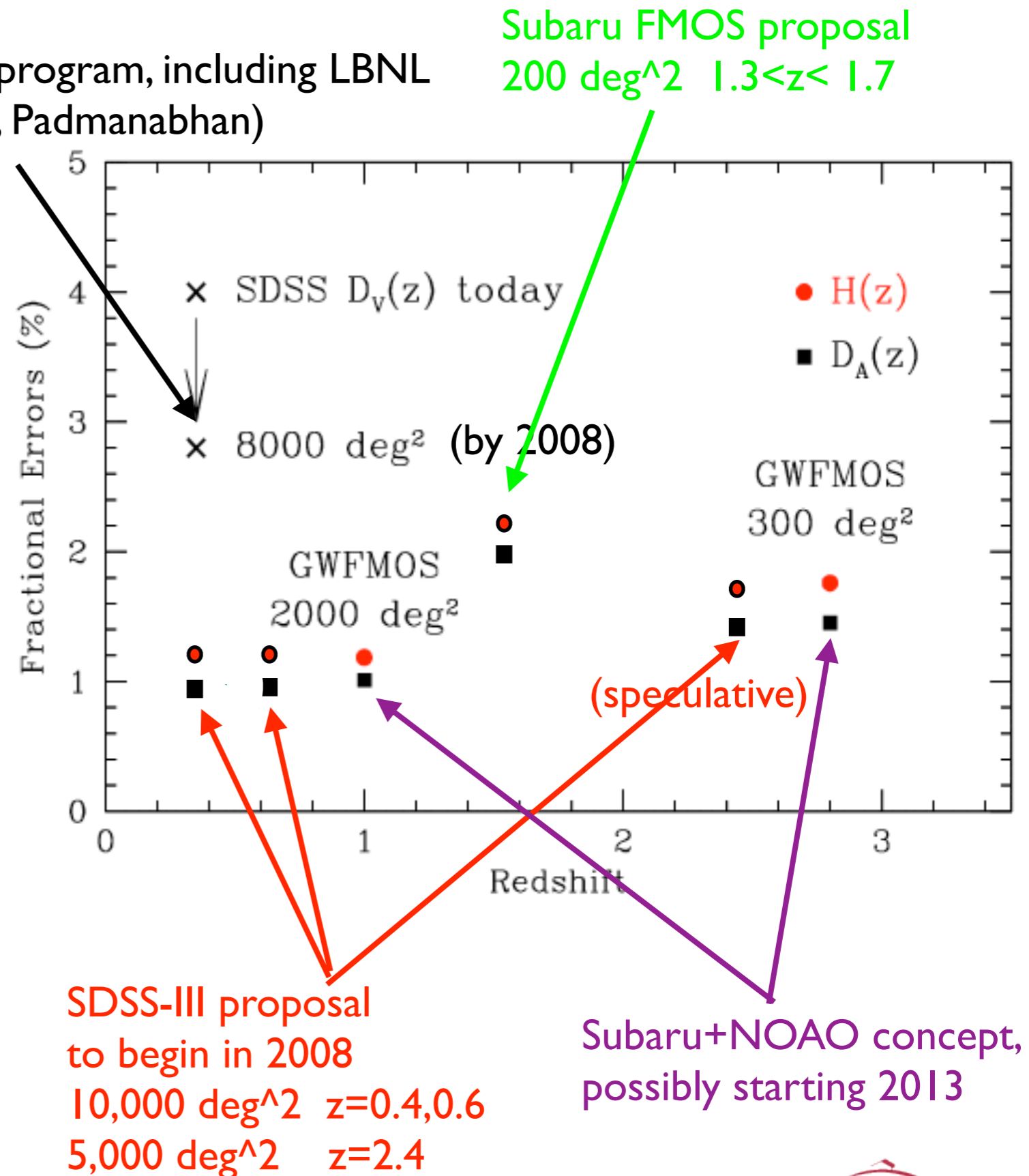
SDSS-III red galaxies  
10,000 deg<sup>2</sup>  
5x sample density (shot noise)  
2x volume

↑  
**PROPOSED**

# Chasing the acoustic peak: SDSS-III

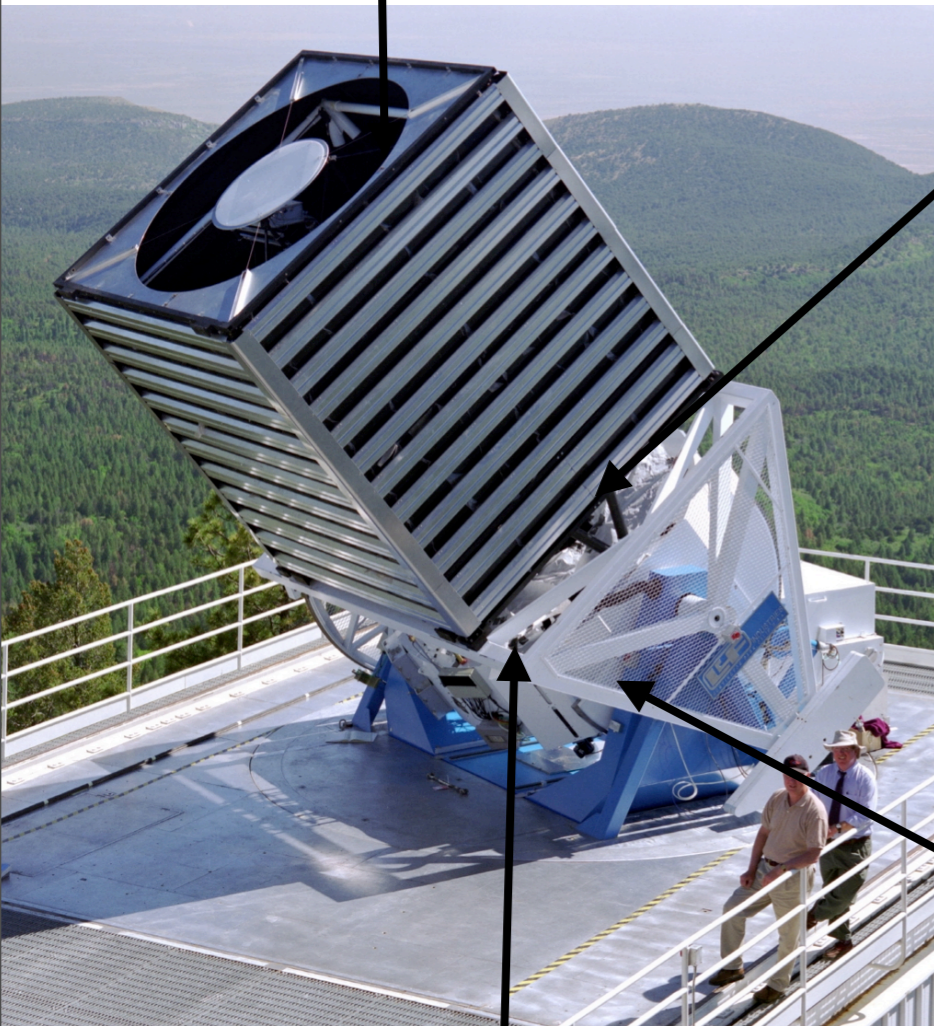
Current program, including LBNL  
(Schlegel, Padmanabhan)

- Proposed ground-based surveys will measure the position of the acoustic peak to high precision.
- Measure distance versus redshift via a robust geometric test.
- SDSS-III will improve the measurement at  $z < 0.8$ , where the dark energy is most dominant.
- SDSS-III may extend to  $z = 2.4$  using quasar absorption lines (speculative)

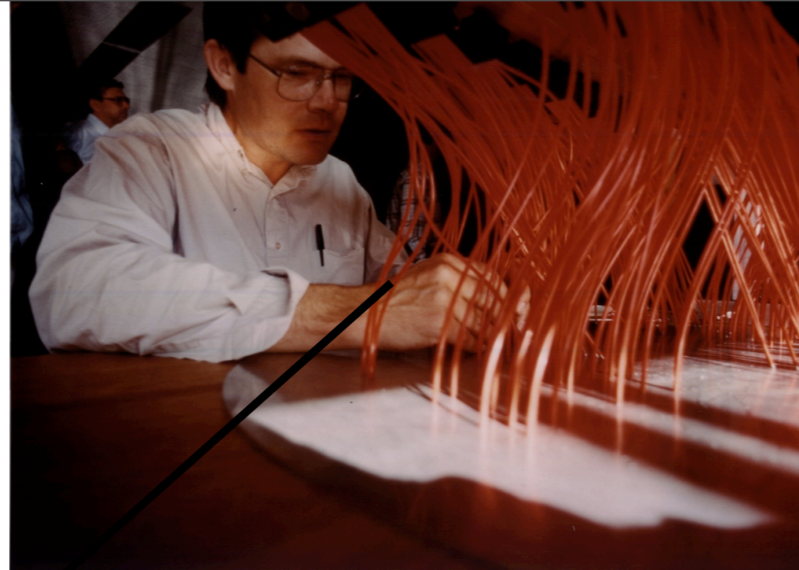


# The Future: SDSS-III

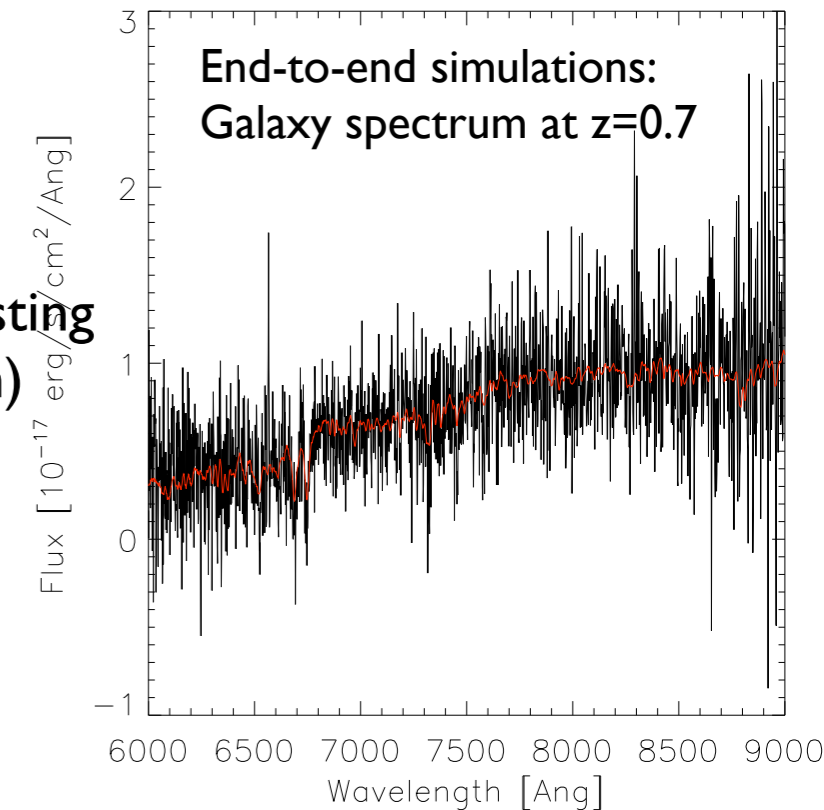
Largest field-of-view of  
any large telescope -- DONE!



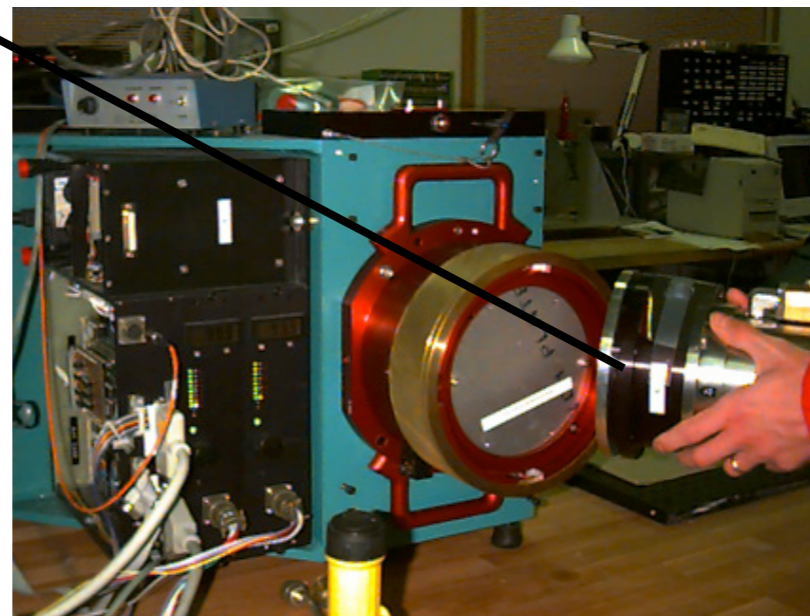
Very efficient spectrographs --  
DONE!



1000 small-core fibers to replace existing  
(more objects, less sky contamination)



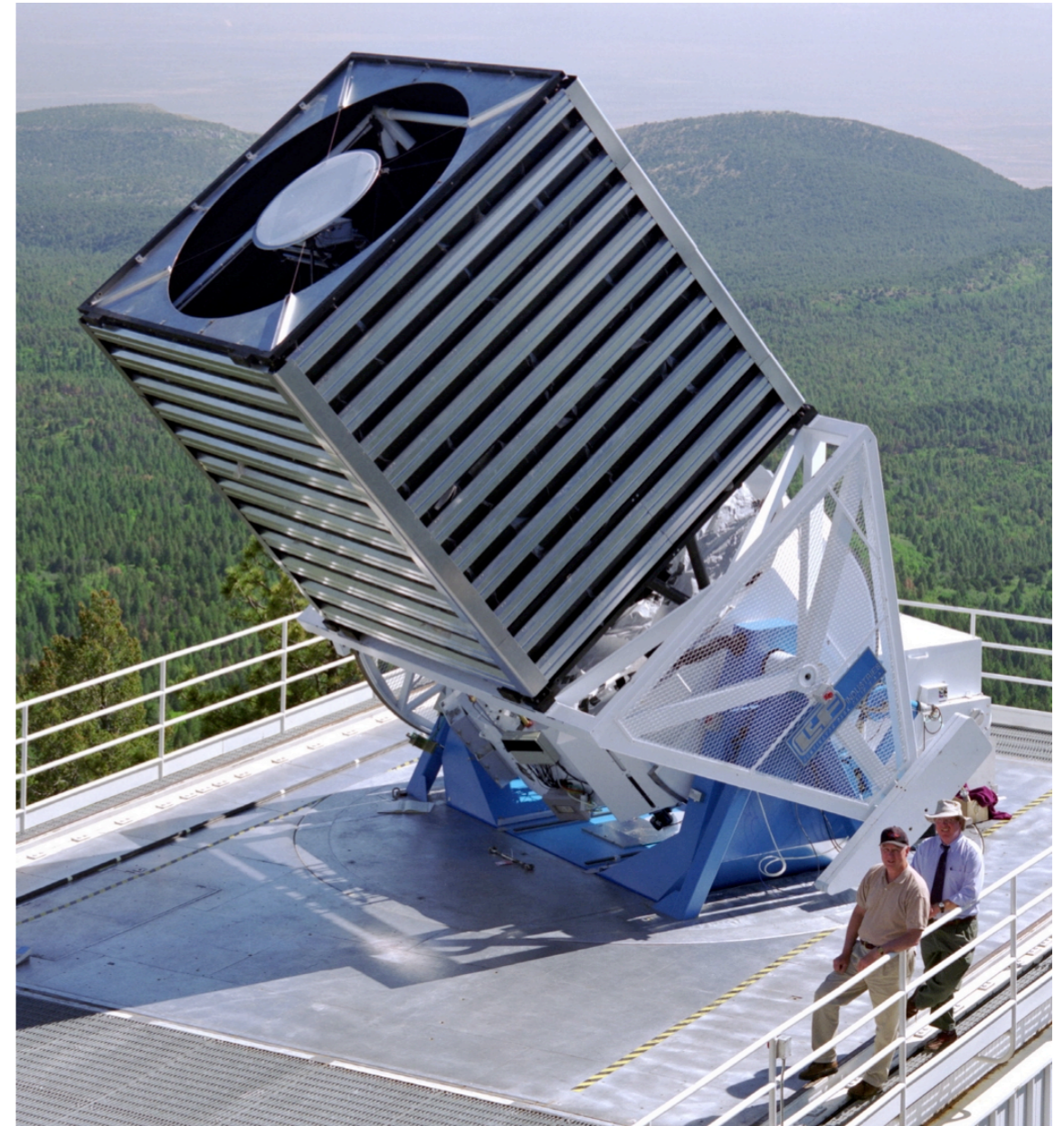
Software development underway  
at LBL, NYU, Princeton



Replace CCDs w/red-  
sensitive LBL/SNAP  
CCDs, making it  
possible to go to  
higher- $z$

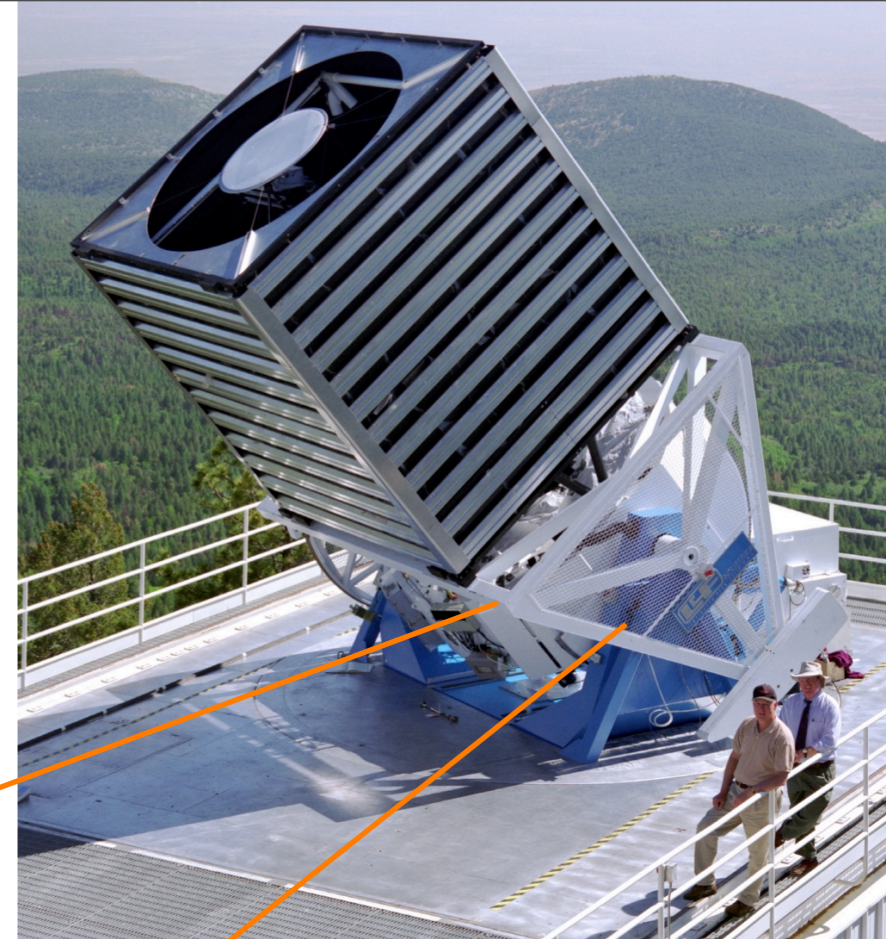
# SDSS-III status

- Current collaborators include LBNL, Princeton, NYU, Arizona, UC Santa Cruz, JHU, U. Washington, U. Chicago, Case Western, Drexel, U. Michigan, MIT, Ohio State
- Design work on new dewars, Princeton
- Design work on new gratings, JHU
- Design work on new optical fibers, U. Washington
- New red CCDs in fabrication, LBNL + Dalsa
- Software development begun at LBNL + NYU (target selection, plate design, data reduction, analysis, databasing), building upon current operations + expertise
- Visit by LBNL to Apache Point Observatory in July to review both hardware + review operating costs
- Plate design code rewrite; **test data scheduled for Nov 2006**
- Proposal to ARC submitted July 31; decision expected 13 Nov 2006; **expect 4 full years of telescope time**
- Collaboration workshop in NYU/Princeton scheduled for 17/18 Nov.; 25 confirmed participants

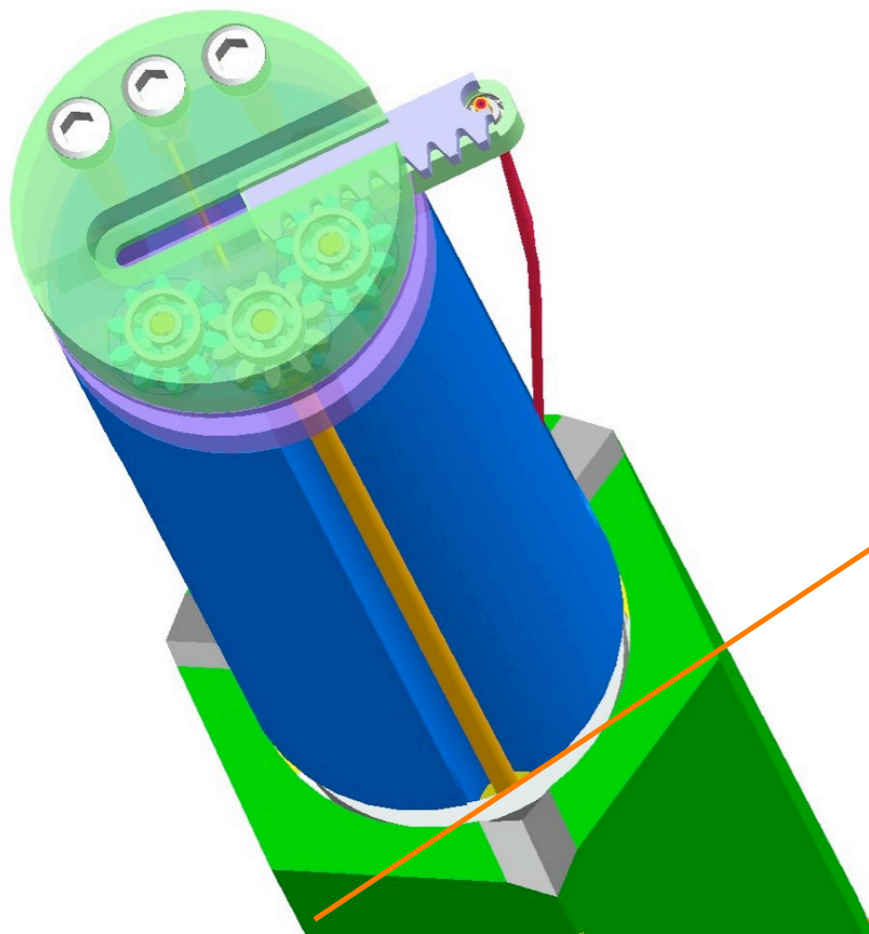


# Future fiber-positioning

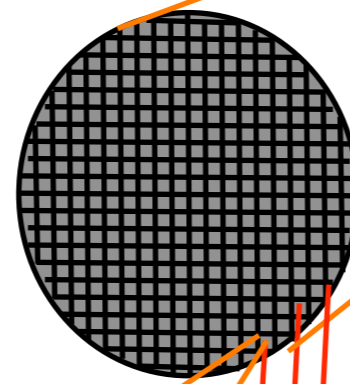
- Supported by Jim Siegrist in 2005/2006, on LDRD starting Oct 2006
- Optimize BAO experiment design, merging Schlegel et al. and Eisenstein & Spergel ideas
- Design + prototype fiber actuators
- Build survey apparatus (*where are the fibers?*)



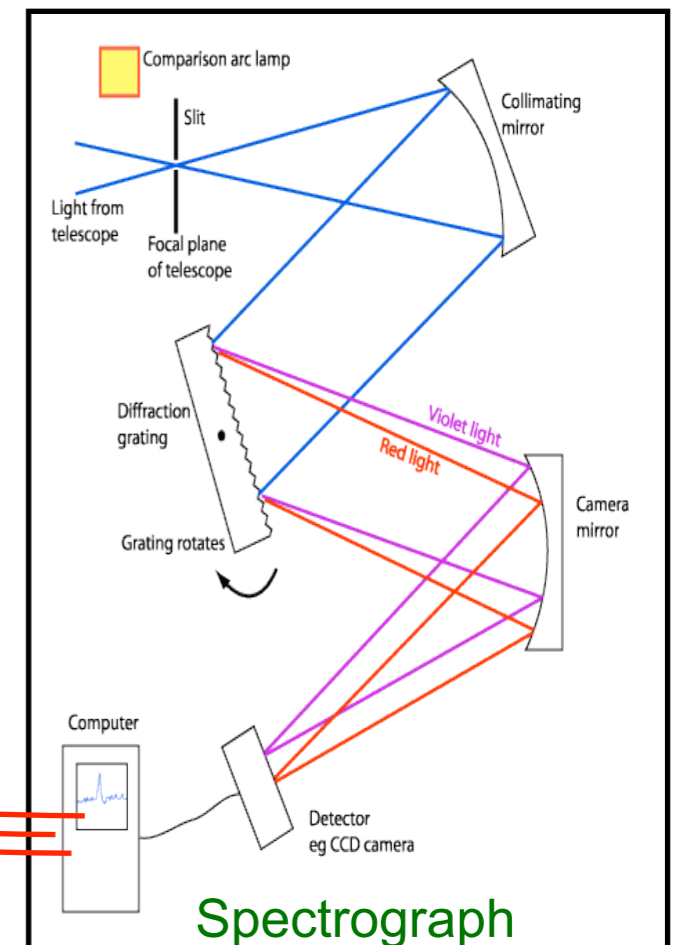
Focal plane



LBNL Fiber Actuator



Optical Fibers



Spectrograph

A Schematic Diagram of a Slit Spectrograph

# Future Directions?

SDSS-III hits limit of 2.5-m telescope

+ old plug-plates “technology”

Future systems will require larger telescopes (Keck 10-m, Subaru 8-m, Spanish 10-m?)

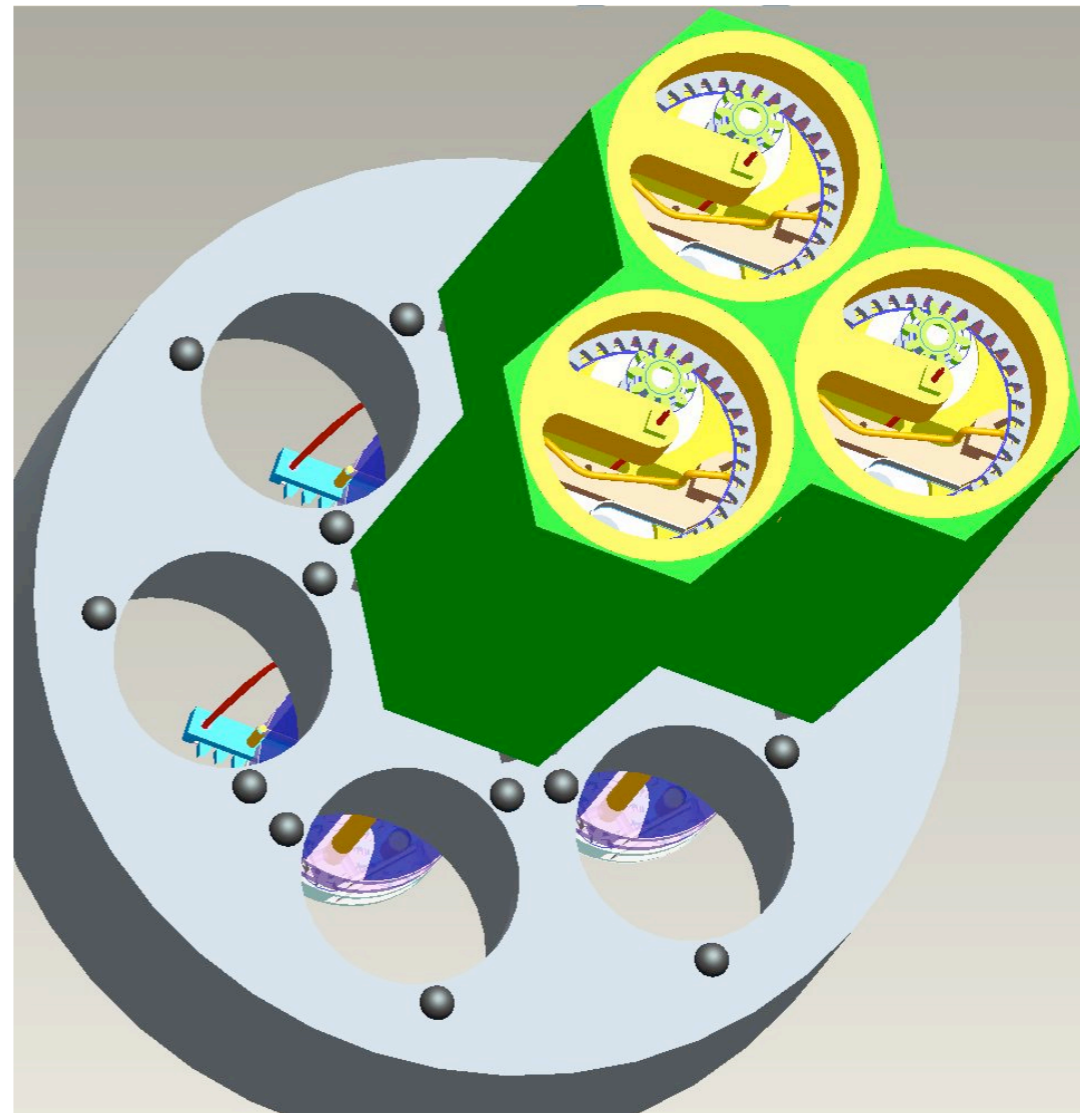
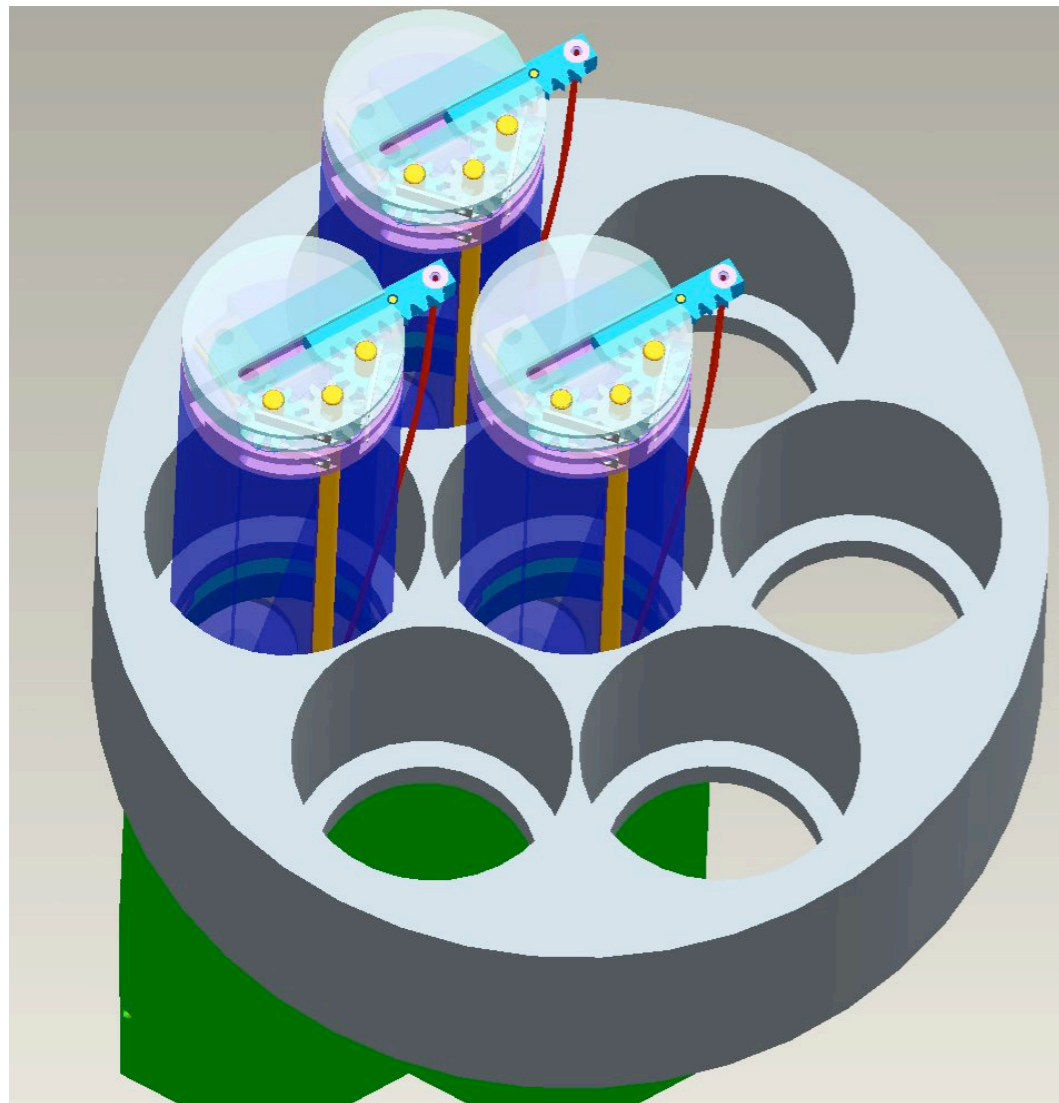
+ automated fiber positioning with  $>1000$  fibers

Huge demand for such technology for ground-based dark energy experiments:

baryon acoustic oscillations, redshifts for weak lensing, kinetic S-Z, ...

Difficult to fund such R&D at Universities. **Thank you LBNL!**

If we don't do this, these future experiments will have to be in space (==**crazy!**)



# Conclusions

- Baryon acoustic oscillations are a rapidly maturing method for measuring the cosmological distance scale and dark energy.
  - Highly robust. Trigonometric method. Errors dominated by sample variance.
  - Complementary to supernova cosmology
- SDSS-3 will be the definitive low-redshift data point, reaching near the cosmic variance limit.
  - Data would also be the best available for large-scale structure, e.g.  $P(k)$ .
  - Possible measurement at  $z=2.5$  from QSOs (speculative)
- Study topics:
  - Observational strategy and instrument flow-down.
  - Parameter estimation in light of reconstruction.
  - How do these distance bounds compete on  $w(z)$ ?
- The future?
  - R&D on fiber-positioning technology for big telescopes; push to higher redshifts  $z>0.7$
  - What is the systematics floor on  $d_A$ ? 1% ? 0.1% ?
  - Study ground-based vs. space-based experiments?